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13281 U.S. PTO

PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c)

INVENTOR(S)		
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TITLE OF THE INVENTION (500 characters max)

PSEUDORANGE RECONSTRUCTION

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ENCLOSED APPLICATION PARTS (check all that apply)

☒	Specification	*Number of Pages:*	9	☐	CD(s), Number	
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METHOD OF PAYMENT OF FILING FEES FOR PROVISIONAL APPLICATION FOR PATENT

☐ Applicant(s) claims small entity status.

☒ A check is enclosed in the amount of **$160.00** for the filing fee.

☒ The Commissioner is authorized to charge any underpayment or credit any overpayment to Deposit Account No. 25-0120

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

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Respectfully submitted,

Docket No.: **1510-1082**

By: Benoit Castel

Benoit Castel, Reg. No. 35,041

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Y&T February 16, 2004

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Pseudorange reconstruction

1 Name Of Invention

Pseudorange reconstruction

2 Inventor

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3 Summary of invention

This invention is in general related to methods for locating user equipment (UE) by using a satellite navigation system like GPS (Global Positioning System), see [1] or [2]. In particular it addresses some specific problems that arises in assisted GPS ([3]) in situations where the initial uncertainty of the location of the UE is large, in a sense that will be described later. Assisted GPS in general aims at improving the performance of GPS receivers in many different respects, including coverage, time to obtain a location estimate, and saving battery power. In general this is done by moving some functionality from the GPS receiver to the network and only perform a subset of the GPS tasks in the receiver itself. However one side-effect is that a rough apriori information about the receiver location is needed to reconstruct certain range measurements that are not completely done by the UE. This invention addresses in particular the problem of range measurement reconstruction in cases where the initial location uncertainty is too large for prior art solutions to work properly. A recursive procedure is proposed where the unlikely range measurements are sequentially discarded based on optimization criteria.

4 Background to the invention

The GPS Space Vehicles (SVs) transmit ranging signals with a spectrum centered at 1575.42 MHz. The signals include a so-called Coarse/Aquisition (C/A) code that is unique for each SV. The C/A code has a length of 1023 chips and a chip duration of $1/1.023\text{x}10^6$ s. The C/A code repeats itself every 1 ms. Superimposed on the C/A code is a navigation data bit stream with a bit period of 20 ms. The navigation data includes among other things a set of so-called ephemeris parameters that enables the receiver to calculate the precise position of the satellites at the time of signal transmisison. The SVs carry precise atomic clocks to maintain clock stability. The SV transmissions are however not perfectly synchronized to GPS system time, as illustrated in the timing diagram **100** of Figure 1. By drawing a vertical line through the timing diagram **100** one may obtain a snapshot of all clock readings as observed in various points in space. GPS system time **101** is defined as an ensemble average based on a set of ground

station clocks and a subset of SV clocks. The individual SV clocks **102, 103** are slightly offset compared to GPS system time. A model for the individual offsets is transmitted as part of the navigation message from each SV. When the signals reach a UE on the earth surface, they have been delayed with an amount depending on the range from the SV in question to the UE. The delay is typically 60-85 ms as illustrated by the clock readings **104, 105**.

The GPS receiver basically measures the pseudorange to a number of satellites. The pseudorange is

$$\rho_i = c\cdot(t_u - t_{ti}) \quad (1)$$

where t_u is the UE clock **106** reading att the time of reception, and t_{ti} is the time of signal transmission of the ith SV (**104, 105**), and c is the wave propagation speed. The pseudorange differs from true range with a number of perturbing factors (receiver clock bias, ionospheric and tropospheric delays, SV clock bias, measurement errors, etc). For the purpose of clarity, in this discussion we will neglect the influence of most of these error sources. There are known techniques to compensate for many of the above listed error sources (see [1], [2]). Furthermore the effect of SV movement and earth rotation is also omitted as it is also well known in the art how to handle these effects. The simplified model is then that the measured pseudodrange obeys

$$\rho_i = |\mathbf{x}_u - \mathbf{x}_{si}| + b + e_i \quad (2)$$

Here $\mathbf{x}_u = (x_u\ y_u\ z_u)$ is a row vector containing the three-dimensional coordinates of the unknown receiver location. Similarly $\mathbf{x}_{si}$ is the row vector containing the coordinates of the ith SV. The notation $|\mathbf{z}|$ means the norm of the vector quantity within brackets, which is equal to $(\mathbf{z}\mathbf{z}^T)^{1/2}$. In this case it can be interpreted as the distance between the receiver and the SV. Furthermore b is the receiver clock bias **106** (expressed as a range),

$$b = c\cdot(t_u - t_{GPS}) \quad (3)$$

where t_{GPS} stands for GPS system time. Finally e_i is the measurement error.

The transmission time t_{ti} is typically determined in several stages. Firstly the submillisecond part of t_{ti} is determined using by determining the boundaries of the C/A codes for each SV (see Figure 1). This is done using correlators that test all possible code phase and Doppler shifts.

In a subsequent step the millisecond part of the transmission time needs to be reconstructed. This normally requires that the received data is despread, leaving raw navigation databits. Timing reconstruction can then be made by a number of techniques.

Direct demodulation of TOW (Time Of Week). This requires first that bit synchronization at 20ms level is done. Then the data is demodulated at a rate of 20ms; this process normally requires that subframe boundaries are determined followed by decoding the so-called Handover Word, from which the TOW, ie the transmission time t_{ti}, can be derived. Each subframe has a length of 6 s, so this procedure may require that approximately 8 seconds of navigation data is collected. TOW demodulation works down to approximately *-172dBW*, assuming *0dB* antenna and is in fact the limiting factor for GPS coverage.

TOW Reconstruction using correlation techniques. This procedure also requires that demodulated data bits are generated, but instead of direct decoding, correlation is made with known transmsmitted navigation data bits (e.g. the contents of the so-called Telemetry Word and the HOW word which may be sent to the UE as part of the assistance data). This requires that the GPS time is apriori known to within a few seconds. This procedure works to somewhat lower signal levels than direct TOW decoding,

but most likely the performance is limited by the tracking loops that may loose lock at such low signal levels. Typically phase locked loops or automatic frequency control loop are employed for this. But it is expected that this will work down to say -179dBW. *Use of real-time clocks.* If TOW has previously been determined the receiver may be able to maintain an accurate clock at a millisecond level using e.g. the cellular system clocks that typically drift only a few nanoseconds per second and long term stability may be better than 1ms for signifiant time. However it may be dificult for the user to know the absolute accuracy, which limits the use of this method.

In MS assisted AGPS [1] the MS reports only the C/A code boundary locations and an estimate of the GPS system time at time of measurement. Oddly enough the MS is requested to report not the millisecond part of the received SV clock, but instead needs to perform a compensation for the assumed propagation delay. It may therefore be assumed that the inaccuracy in the time stamp could typically be larger than 1ms. There are techniques for estimating the propagation delay down to millisecond level, listed in the copending application.

A further possibility is that the MS does not try to estimate GPS system time at reception time at ms accuracy level. Instead one may use redundant measurements for estimating also the unknown reception time.

The MS in MS assisted AGPS reports only pseudoranges modulo 1 C/A code period, ie the integer number of code periods in the pseudorange (1) is not known. It has to be reconstructed. Let

$$R = c \cdot 10^{-3} \tag{4}$$

denote the range corresponding to one C/A code period. We thus have that

$$\rho_i = k_i R + \nu_i \tag{5}$$

where ν_i is the reported measurement that satisfies $0 \leq \nu_i < R$, and where admissable values of the integer k_i needs to be reconstructed. The reconstruction is done in the following way. It is assumed that an apriori location $\mathbf{r}_{u0}$ of the MS is known, along with an uncertainty Δ, such that

$$|\mathbf{x}_u - \mathbf{x}_{u0}| < \Delta \tag{6}$$

First we determine the predicted pseudorange, and divide into an integer C/A part and a fractional part

$$\rho_i' = |\mathbf{x}_{si} - \mathbf{x}_{u0}| = k_i' R + \nu_i' \tag{7}$$

where k_i' is an integer and ν_i' satisfies $0 \leq \nu_i < R$. We then define the reconstructed pseudorange as

$$\rho_i^* = k_i^* R + \nu \tag{8}$$

and take $k_i^* = k_i'$ as initial value. Next if $\rho_i^* - \rho_i' > R/2$, then we set $k_i^* = k_i^* - 1$. Else if $\rho_i^* - \rho_i' > R/2$ then we set $k_i^* = k_i^* + 1$.

When the initial location uncertainty is large, several values of k_i may be admissable. Furthermore the presence of a common bias term b makes it difficult to reconstruct the k_i exactly. However from position calculation point of view it is the relative pseudoranges that matter, since any constant bias term will cancel in the position calculation. Therefore it is desirable to obtain a bound on admissable relative pseudoranges, given the amount of initial location uncertainty. Assuming small meaurement errors, we have that

$$\rho_i\text{-}\rho_1=|x_u\text{-}x_{si}|\text{-}|x_u\text{-}x_{s1}| \tag{9}$$

To obtain a sharp bound one may calculate the expected range difference at all possible receiver locations that satisfy (6). This way we obtain an inequality

$$-\Delta_i \leq \rho_i\text{-}\rho_1 - \delta\rho_i \leq \Delta_i \tag{10}$$

where $\delta\rho_i$ is the mean value of the maximum and minimum range difference that was found within the uncertainty area. Similarly Δ_i is half the difference between the maximum and minimum range difference that was found within the uncertainty area. $\rho_1{}^*$ can now be calculated using (8), and an initial value of $\rho_i{}^*$ is obtained using the same formula (8). Then it can be checked for varying $k_i{}^*$, whether the (10) is satisfied..

However it may be cumbersome to determine $\delta\rho_i$ and Δ_i explicitly. A simpler way is base the calculations on the individual pseudoranges. Similarly to (10) one may determine ρ_i' and Δ_i that fulfil

$$-\Delta_i \leq \rho_i\text{-}b\text{-}\rho_i' \leq \Delta_i \tag{11}$$

for all x_u that satisfy (6). This can be done quite easily by applying simple geometry. Applying the triangle inequality one may then obtain

$$|\,(\rho_i\text{-}b\text{-}\rho_i')\text{-}(\rho_1\text{-}b\text{-}\rho_1')| \leq |\,(\rho_i\text{-}b\text{-}\rho_i')|+|(\rho_1\text{-}b\text{-}\rho_1')| \leq \Delta_i+\Delta_1 \tag{12}$$

A further simplifying expression may be obtained by using only the relation (6) and the triangle inequality. First note that

$$||x_u\text{-}x_{si}|\text{-}|x_u\text{-}x_{s1}|| \leq |x_u\text{-}x_{si}|+|x_u\text{-}x_{s1}| \tag{13}$$

hence

$$\rho_i\text{-}b=|x_u\text{-}x_{si}|=|(x_u\text{-}x_{u0})\text{-}(x_{si}\text{-}x_{u0})| \leq |x_u\text{-}x_{u0}|+|x_{si}\text{-}x_{u0}| \leq \Delta+\rho_i' \tag{14}$$

Secondly note that the triangle inequality also gives that

$$|\,|(x_{si}\text{-}x_{u0})|\text{-}|(x_u\text{-}x_{u0})|\,| \leq |x_u\text{-}x_{si}| = \rho_i\text{-}b \tag{15}$$

Since the distance to the SVs are most likely larger than the uncertainty in location we get that

$$\rho_i'\text{-}\,\Delta \leq \rho_i\text{-}b \leq \rho_i'+\Delta \tag{16}$$

Rearranging we get that

$$-\,\Delta \leq \rho_i\text{-}b\text{-}\rho_i' \leq \Delta \tag{17}$$

hence

$$|\rho_i - b - \rho_i'\,| \leq \Delta \tag{18}$$

The relative pseudorange errors are then bounded by

$$|\,(\rho_i - b - \rho_i')\text{-}(\rho_1 - b - \rho_1')\,| \leq |\,\rho_i - b - \rho_i'\,|+|\,\rho_1 - b - \rho_1'\,| \leq 2\Delta \tag{19}$$

Equatons (10), (12) and (19) define three ways to find admissable values for $k_i{}^*$. This is done by replacing the true pseudorange ρ_i by the reconstructed $\rho_i{}^*$, and varying $k_i{}^*$ in the expression (8). In

order to have a unique reconstruction of pseudorange it is thus required that only one k_i^* satisfies the inequalities (10), (12), (19). The possible pseduorange values of the left hand side are in all cases spaced by R meters. The width of the uncertainty interval for the last example (19) is 4Δ. So for this case an unique k_i^* is found whenever $\Delta < R/4$.

5 Problem

It has been demonstrated above that a unique reconstruction of pseudoranges may in worst case require that the initial location uncertainty is less than R/4. This amounts to approximately 75 km. There are several cases where it can be assumed that the initial location is not known to that accuracy level. In most cellular standards the initial location and its associated uncertainty is given by the coverage of the serving cell. In GSM the cells may be as large as 100km in so-called extended range mode. For some other applications, it may be foreseen that the MS location is not known at a cell level, perhaps only the Service Area or Location area is known. These areas cover more than one individual cell and may therefore span larger areas than 75km. In other extreme cases maybe only the country of the visitited network operator is known. It is therefore desirable to be able to cope with the situation where the initial location uncertainty may cause ambiguities in the reconstruction of pseudoranges.

6 Solution

Before we present the solution in detail we will describe the position calculation function in detail. First we express the measurement equation (2) in vectorized form as

$$\rho = |\mathbf{1}_n \cdot \mathbf{x}_u - \mathbf{X}_s| + b + e \qquad (20)$$

Here ρ is the column vector of length n containing the pseudoranges, $\mathbf{1}_n$ is a column vector of length n containing only ones. $\mathbf{X}_s$ is a matrix where the ith row contains the coordinates $\mathbf{x}_{si}$ of the ith SV. It is assumed here that the norm $|\mathbf{Z}|$ is calculated for each row of the matrix $\mathbf{Z}$ within brackets.

We may now perform a Taylor series expansion around the inital estimate of the unknown parameters $\mathbf{x}_u$ and b.

$$\rho = |\mathbf{1}_n \cdot \mathbf{x}_u - \mathbf{X}_s| + b + e = |\mathbf{1}_n \cdot \mathbf{x}_{u0} - \mathbf{X}_s| + \mathbf{G} \cdot ((\mathbf{x}_u - \mathbf{x}_{u0})\ b)^T + \mathbf{v} \qquad (21)$$

$\mathbf{G}$ is the geometry matrix which contains the derivatives of the pseudoranges with respect to the parameters $\mathbf{x}_u$ and b. Let

$$r_i = |\mathbf{x}_{u0} - \mathbf{x}_{si}| \qquad (22)$$

then $\mathbf{G}$ is a matrix with the ith row being equal to

$$\mathbf{G}_i = [(x_{u0} - x_{si})/r_i \quad (y_{u0} - y_{si})/r_i \ (z_{u0} - z_{si})/r_i \quad 1] \qquad (23)$$

Note that since $|\mathbf{1}_n \cdot \mathbf{x}_{u0} - \mathbf{X}_s| = \mathbf{G}(:,1:3) \cdot \mathbf{x}_{u0}^T$, (21) may be simplified to

$$\rho = \mathbf{G} \cdot (\mathbf{x}_u \ \ b)^T + \mathbf{v} \qquad (24)$$

The least squares solution to (24) is equal to

$$(\mathbf{x}_u \ \ b)^T = (\mathbf{G}^T\mathbf{G})^{-1}\mathbf{G}^T\rho \qquad (25)$$

The least squares minimum loss function value, is equal to

$$V = \rho^T(\mathbf{I} - \mathbf{G}(\mathbf{G}^T\mathbf{G})^{-1}\mathbf{G}^T)\rho \qquad (26)$$

The minimum loss function value is a meaure of how well the predicted pseudoranges based on an updated parameter estimate, match the measured pseudoranges.

Returning now to the problem of pseudorange reconstruction, the complete procedure is outlined in Figure 2. The procedure starts at **201** by calculating a reconstructed pseudorange for an arbitrary *SV*. Let this pseudorange be denoted ρ_1*. The we compute admissable pseudoranges ρ_2* and ρ_3* using (10), or (12), or (19). Assuming n_2 and n_3 admissable pseudoranges were found, respectively, then $n_2 \cdot n_3$ candidate pseudorange vectors can be constructed. In **202** a least squares estimate is performed for each candidate, but since only three measurements are used, only a two dimensional location fix can be made. It is most natural to estimate the x and y coordinates since the apriori uncertainty in the vertical dimension is typically smaller than the horizontal uncertainty. Therefore the third column of the **G** matrix is not used, and we need to use (21) instead of (24), since the simplification leading to equation (24) is not valid in that case.

The reduced parameter vector $(x_u\ y_u\ b)^T$ is estimated for all candidate pseudorange vectors. In **203** the selection of the most pseudorange vector candidate is done by considering the size of the update step in the horizontal dimension. Hence $((x_u - x_{uo})^2+(y_u - y_{uo})^2)^{1/2}$ is determined for all candidate vectors. Since it is known that apriori $((x_u - x_{uo})^2+(y_u - y_{uo})^2)^{1/2} < \Delta$ for the true parameter vector x_u , y_u those candidates that generate an update step significantly larger than Δ are excluded from further calculations. The threshold should be chosen somewhat larger than Δ to acount for the fact that the least squares solution normally has to be performed iteratively, with an updated G matrix, since the least squares equation (25) is only an approximation for the original non-linear problem (20). Note that in this case the residual V in (26) cannot be used, since it will in most cases be equal to zero in the case of three measurements, three equations.

In the next step **204** it is checked whether all pseudoranges have been reconstructed. If yes, the position calculation function **213** is used for calculation of the UE position. If no, in next step **205** all candidate pseudoranges ρ_4* are calculated using either (10), (12), or (19), and a set of all possible pseudorange vectors is constructed. In **206**, the loss function value (26) is calculated for all candidate pseudorange vectors, assuimg also in this case that only a two-dimensional location vector is estimated. Note that in this step no explicit solution (25) needs to be calculated. In **207**, the pseudorange vector that minimized the loss function is kept. Alternatively all vectors that produce a loss function less that a certain threshold is kept.

In the next step **208** it is checked whether all pseudoranges have been reconstructed. If yes, the position calculation function **213** is used for calculation of the UE position. Otherwise, in the following steps, enough measurements are available to enable a three-dimensional solution. The procedure for pseudorange construcution is thus repeated in **209** for ρ_k* where k=5. The loss function values is computed in **210** for all admissabe pseudorange vectors using (26) with the complete G matrix. The most unlikely pseudorange vectors are excluded in step **211** based on the said loss function values. In step **212** it is checked whether all pseudoranges have been reconstructed. If yes, the position calculation function **213** is used for calculation of the UE position. Otherwise the procedure of pseduorange reconstruction and exclusion of unlikely pseudorange vectors is repeated from step **209** for ρ_k* where *k* is incremented before each new iteration of **209-211**. When all pseduoranges have been resonstructed, the least squares solution (25) is determined in step **213**, possibly using an iterative scheme.

In Figure 3, an exemplary hardware implementation is shown. The UE **300** consists of a cellular communication module **301**, a positioning module **302**, an GPS RF front end **303**, an antenna **304** for communication with the cellular network and a GPS antenna **305**. The cellular communication module **301** receives assistance data from the cellular network. The assistance data could consist of ephemeris

and clock corrections for visible satellites, an approximate UE location and an approximate GPS system time. Alternatively the assistance data could contain explicit assistance intended only for assisting the correlation processing. The assistance data is in both cases sent to the positioning module **302** using the interface **306**. The communication module **301** also provides the GPS RF front end **303** and the positioning processor **302** with a clock reference **307**. The RF front end module **303** is controlled by the positioning processor **302** using interface **308**. When the positioning module **302** receives a positioning request from the communication module **301**, it instructs the RF front end module **303** to collect GPS signal samples. The GPS RF front end **303** receives the GPS frequency band through the antenna **305**, downconverts the signal to baseband, separates the signal into in-phase (I) and quadrature (Q) components, samples and converts the signals into digital format, and outputs these to the positioning processor **302** through interface **309**. The positioning processor stores the received I and Q data in memory **310** and after enough data has been collected, correlation operators take place within the DSP **311**. After finding at least one correlation peak corresponding to at least one satellite signal, the said signal is despread leaving raw navigation data bits, and the TOW at reception is estimated using any of the techniques described herein. The correlators are controlled by the CPU **312**, that in turn uses the assistance data for reducing the amount of correlations needed. When enough C/A code boundaries have been detected, or a timer has elapsed, the positioning module **302** outputs the measured truncated pseudoranges and the estimated TOW to the communication module **301** through the interface **313** that sends the measurements to the cellular network for pseudorange reconstruction and position calculation. Alternatively the pseudorange reconstruction and position calculation may be done in the CPU **312** using available ephemeris and clock correction parameters, approximate GPS system time and the approximate location of the UE.

7 Claims Proposal

1. A method for calculation of the location of a user equipment, being able to communicate with a cellular network, user equipment including a GPS receiver, being characterized by;
- the initial user location being known to be within a specified inital uncertainty area, e.g. as a geographical point with an uncertainty circle.
- the receiver estimating the truncated pseudorange to a multiple of satellites, by determining the code boundaries of signals transmitted by said multiple satellites.
- the receiver may optionally reconstruct the complete pseudoranges for some, but not all satellites, using a despread satellite signal.
- a position calculation functionality wherein the complete pseudoranges are reconstructed for all satellites for which only truncated pseudoranges are available.
- a position calculation functionality that calculates all possible pseudoranges in situations where the initial uncertainty area is too large to enable unique reconstruction of the said pseudoranges
- a position calculation functionality that performs location calculations based on all admissable pseudorange vectors, and based on the result of the position calculation, determines the most likley pseudoranges.
- a position calculation functionality that based on the most likely pseudoranges, determines the location of the user equipment.

2. A method according to 1, further characterized by,
- the set of admissable pseudoranges being determined by first calculating the range to the center of the initial uncertainty area, and the lower and upper bounds for the range being approximated by using the radius of the initial uncertainty area.

3. A method according to 1, further characterized by,

- the set of admissable pseudoranges are being determined by calculating the smallest and largest range from each satellite to any point within the initial uncertainty area.

4. A method according to 1, further characterized by,
- the set of admissable pseudoranges being determined by calculating the smallest and largest range difference between any satellite and a reference satellite to any point within the initial uncertainty area.

5. The method according to 1, further characterized by,
- the set of admissable pseudorange vectors being determined for 3 satellites,
- a set of possible locations in the horizontal coordinates being determined using the set of admissable pseudoranges
- the set of admissable pseudoranges being reduced by excluding those pseudorange vectors that led to a horizontal location coordinate sufficiently outside the initial uncertainty area.

6. The method according to 5, further characterized by,
- the set of admissable pseudoranges being determined for a 4th satellite, if such measurement is available
- the location in the horizontal coordinates being determined using the set of admissable pseudorange vectors,
- a so-called loss function value, a measure of how well the 4 pseudoranges match, is calculated at all determined locations
- the set of admissable pseudoranges being reduced by excluding those pseudorange vectors that produced a too large loss function value

7. The method according to 6, further characterized by,
- the set of admissable pseudoranges being determined for the 5th satellite, is such measurement is available
- the location in three-dimensional coordinates being determined using the set of admissable pseudorange vectors,
- a so-called loss function value, a measure of how well the 5thpseudoranges match, is calculated at all determined locations
- the set of admissable pseudoranges being reduced by excluding those pseudorange vectors that produced a too large loss function value

8. The method according to 7, further characterized by,
- the procedure of claim 7 is repeated for satellites 6 to n, where n is the number of satellites being measured by the GPS receiver.

9. The method of claim 8, further characterized by,
- the position calculation functionality residing in the cellular network or any node external to the user equipment.

10. The method of claim 8, further characterized by,
- the position calculation functionality residing in the user equipment.

8 References

[1] Navstar GPS Space Segment/Navigation user Interfaces, ICD-GPS-200, Revision IRN-200C-003, 11 October 1999.

[2] Parkinson, Spilker Global Positioning System: Theory and Applications, Volume 1, AIAA, 1996

[3] 3GPP TS 44.031, v 5.6.0

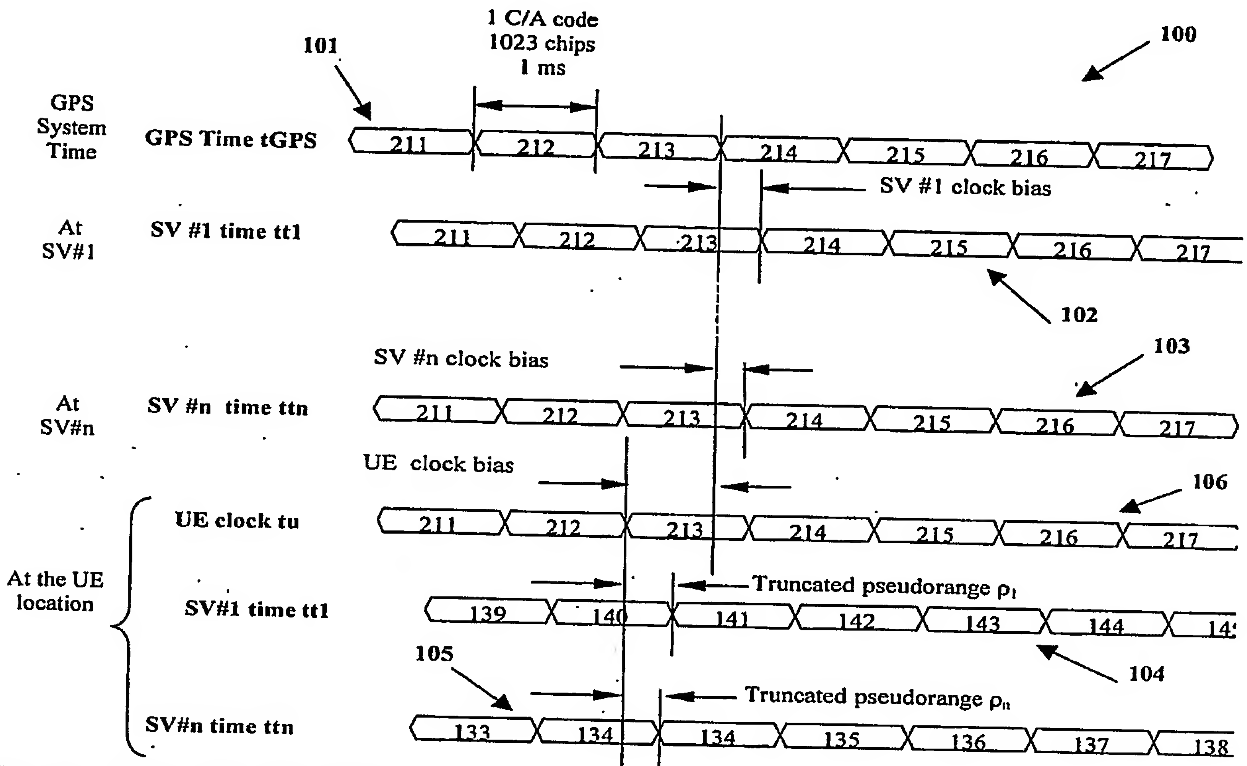

Figure 1. GPS clock definitions

Prepared (also subject responsible if other)		No.		
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Approved	Checked	Date	Rev	Reference
EAB/TUD/P [Ari Kangas]		2004-02-12	A	

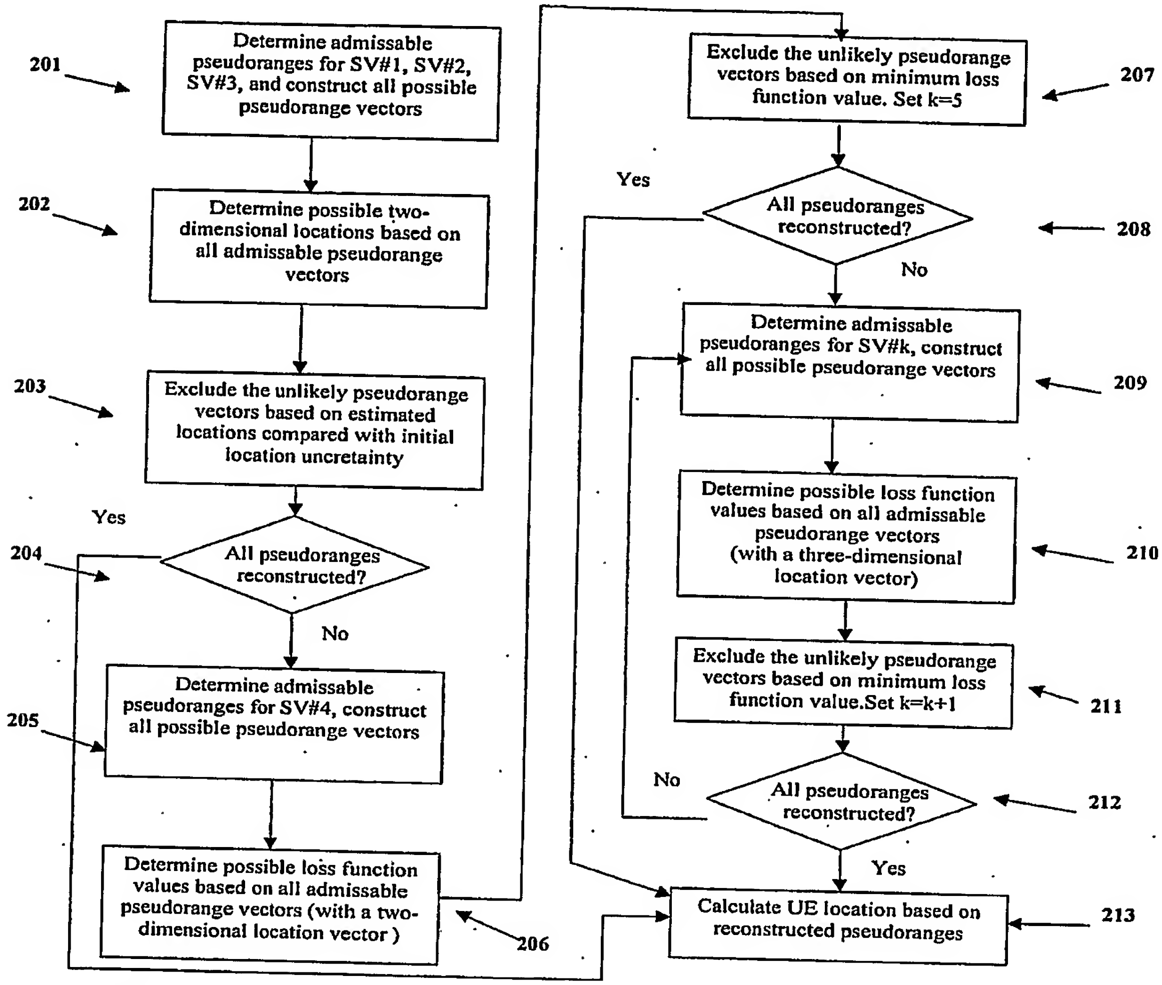

Figure 2. Work flow for pseudorange reconstrcution

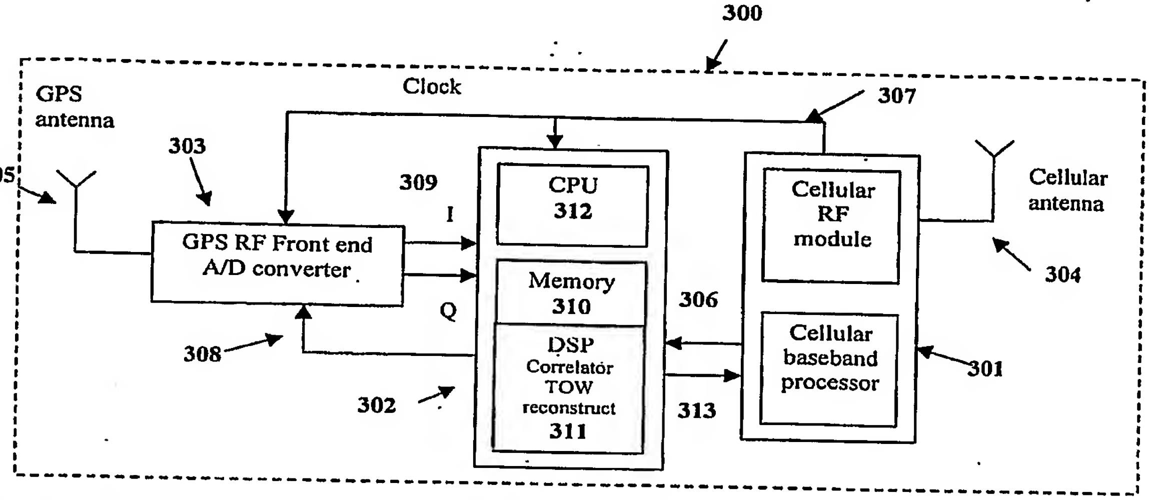

Figure 3. Exemplary implementation